APPENDIX C

SACRIFICIAL CATHODIC PROTECTION SYSTEM BASIC DESIGN FORMULAE AND REFERENCE TABLES FOR CIVIL WORKS APPLICATIONS

A study was performed to characterize the resistance and hence current output for the most common shapes and sizes of sacrificial anodes. Multiple measurements were taken at remote earth in waters with resistivity of 1250 ohm-cm and 4550 ohm-cm. The results are summarized in Figure C-1.* Table C-1 provides the average resistance values obtained on each of the two anode types that were evaluated. The anode specimen numbers were developed to indicate the dimensions of each anode, in in., with each dimension being separated by an "x", followed by the anode style ("R" for round and "S" for slab), and then the edge condition ("BE" for bare edge and "CE" for coated edge). All anodes are coated on their back surfaces.

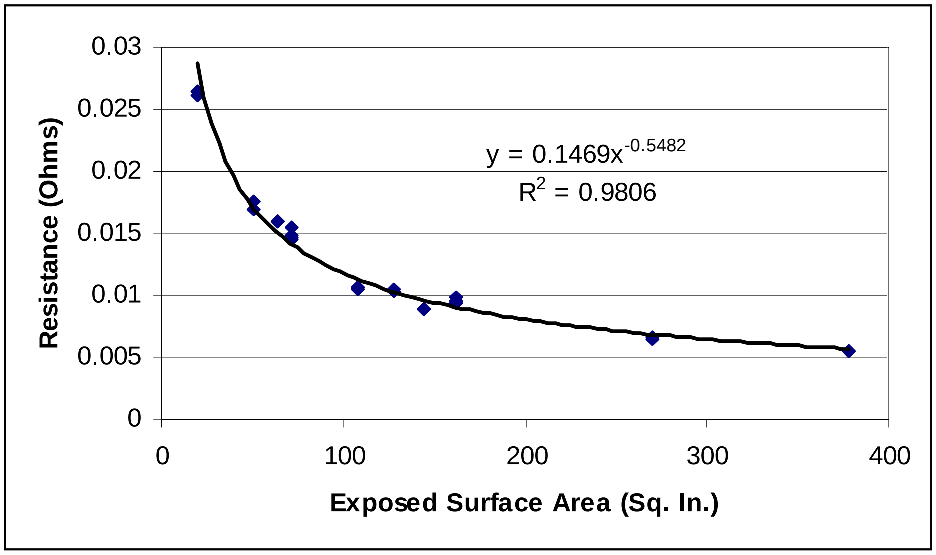


FIGURE C-1. RESISTANCE VS ANODE SURFACE AREA NORMALIZED FOR 1 OHM-CM RESISTIVITY WATER

* Marsh, Charles P., and J. B. Bushman, "Direct Determination of Galvanic Anode Current Output for Common Shapes Used In Civil Works Applications," presented to the Tri-Service Corrosion Conference (21 November 2003, Las Vegas, NV).

TABLE C-1. CURRENT OUTPUT FOR RECOMMENDED ALLOYS OF MAGNESIUM AND ZINC IN 1 OHM-CM RESISTIVITY WATER

Anode Style No.	Anode Type	Current output in 1 ohm-cm Water using high-potential Mag (milliamperes)	Current output in 1 ohm-cm Water using H-1 Alloy Mag (milliamperes)	Current output in 1 ohm-cm Water using high-purity Zinc (milliamperes)
2x5RBE	Button	55,882	41,176	14,706
2x5RCE	Button	33,101	24,390	8,711
1x6x12SBE	Slab	84,070	61,947	22,124
1x6x12SCE	Slab	67,375	49,645	17,731
2x8x8SBE	Slab	92,233	67,961	24,272
2x8x8SCE	Slab	63,333	46,667	16,667
2x6x12SBE	Slab	98,958	72,917	26,042
2x6x12SCE	Slab	67,376	49,645	17,731
2x9x18SBE	Slab	139,706	102,941	36,765
2x9x18SCE	Slab	105,556	77,778	27,778
4x9x18SBE	Slab	166,667	122,807	43,860
4x9x18SCE	Slab	105,556	77,778	27,778

The current output calculations in Table C-1 are based on the structure being protected to a polarized potential of -0.85 volt with respect to a $Cu-CuSO_4$ reference electrode. Further, the values for each alloy are based on the most commonly used potential values for each alloy versus Cu-CuSO4 reference electrode of -1.80 volts for high-potential alloy magnesium, -1.55 Volts for H-1 alloy magnesium (Grade A or B only) and -1.1 Volts for high-purity Zinc.

Table C-2 provides the approximate weight of each anode style in both magnesium and zinc alloys. Because the life of any galvanic anode is directly proportional to its weight and inversely proportional to its current output, both values must be known to calculate anode life.

TABLE C-2. APPROXIMATE ANODE WEIGHT

Anode Style No.	Anode Type	High-Potential And H-1 Alloy Magesium Anode Weight (Pounds)	High-Purity Zinc Anode Weight (Pounds)
2x5RBE	Button	2.5	10
2x5RCE	Button	2.5	10
1x6x12SBE	Slab	5	22
1x6x12SCE	Slab	5	22
2x8x8SBE	Slab	7.5	30
2x8x8SCE	Slab	7.5	30
2x6x12SBE	Slab	10	42
2x6x12SCE	Slab	10	42
2x9x18SBE	Slab	24	95
2x9x18SCE	Slab	24	95
4x9x18SBE	Slab	44	175
4x9x18SCE	Slab	44	175

Given the above information, the current output for any of the evaluated anode styles in different electrochemical environments can be calculated using the following formula

$$I_a = \frac{I_{alloy1}}{P}$$

where:

I_a = current output of anode in water surrounding structure to be protected

I_{alloy1} = current output of anode metal alloy selected from Table 2 in 1 ohm-cm water (in milliamperes)

P = measured resistivity of water surrounding structure to be protected

As an example, for a lock gate immersed in 2700 ohm-cm water, the current output using a 2x9x18SBE high-potential magnesium alloy anode would be:

$$\frac{139{,}706}{2700} = 51.74mA$$

If H-1 magnesium alloy were used instead, the current output for this same style anode would be:

$$\frac{102{,}941}{2700} = 38.13mA$$

If high-purity zinc alloy were used instead, the current output for this same style anode would be:

$$\frac{36{,}765}{2700} = 13.62mA$$

Because the amount of bare submerged metal that can be protected is directly proportional to the current output of the anode, it can be seen that the high-potential magnesium alloy can protect 1.36 times as much surface area as the H-1 magnesium alloy and 3.8 times as much surface area as the high-purity zinc alloy.

Another consideration in anode selection is that the life of each anode is inversely proportional to the current output of the anode. Two different formulae, one for magnesium-based alloys and another for zinc-based alloys, are used for calculating anode service life. For magnesium-based anodes, the following formula applies:

$$Life_{mag(years)} = \frac{116 \times W \times E \times UF}{I}$$

where:

$Life_{mag(years)}$ = years before anode is consumed to the point where its size has been reduced substantially by corrosion and its current output has reduced to the point where it is no longer considered an effective anode.

W = weight of magnesium metal in anode

E = efficiency in converting corrosion current to cathodic protection current = 50% for magnesium

UF = percentage anode used before it is no long considered an effective anode = normally 85% for any galvanic anode

I = current output of single anode in milliamperes

For the 2x9x18SBE high-potential magnesium alloy anode example given above, installed in 2700 ohm-cm resistivity water, the life of the anode would be:

$$Life_{mag(years)} = \frac{116 \times 24 \times 0.5 \times 0.85}{51.74}$$

$$Life_{mag(years)} = 22.9$$

For the same anode using H-1 alloy magnesium, the 2x9x18SBE style anode installed in 2700 ohm-cm resistivity water, the life of the anode would be:

$$Life_{mag(years)} = \frac{116 \times 24 \times 0.5 \times 0.85}{38.13}$$

$$Life_{mag(years)} = 31.0$$

As noted above, a slightly different formula is used for zinc anodes:

$$Life_{zinc(years)} = \frac{42.4 \times W \times E \times UF}{I}$$

$Life_{mag(years)}$ = years before anode is consumed to the point where its size has been reduced substantially by corrosion and its current output has reduced to the point where it is no longer considered an effective anode.

W = weight of zinc metal in anode

E = efficiency in converting corrosion current to cathodic protection current = 90% for zinc

UF = percentage anode used before it is no long considered an effective anode = normally 85% for any galvanic anode

I = current output of single anode in milliamperes

Therefore, for the same anode using high-purity zinc alloy, the 2x9x18SBE style anode installed in 2700 ohm-cm resistivity water, the life of the anode would be:

$$Life_{Zinc(years)} = \frac{42.4 \times 95 \times 0.9 \times 0.85}{13.62}$$

$$Life_{Zinc(years)} = 226$$

Given the anode lives calculated for each of the three examples, if a 20 year design life were desired, the high-potential Alloy would not be acceptable in water of this resistivity while the H-1 Alloy would have the desired life. The life of the high-purity zinc alloy anode in this style would be considered excessive, and an alternative style would be considered if zinc were the preferred anode material. However, as explained below, it should be noted that zinc anodes are not recommended for use in water exceeding 2500 ohm-cm resistivity.

Because the anode efficiencies for zinc and magnesium are known to be 0.9 and 0.5, respectively, and because a utilization factor of 0.85 is almost always applied by corrosion engineers in designing systems, a simple graph of anode life versus current output can be made for magnesium (Figure C-2) and zinc (Figure C-3) alloy anodes.

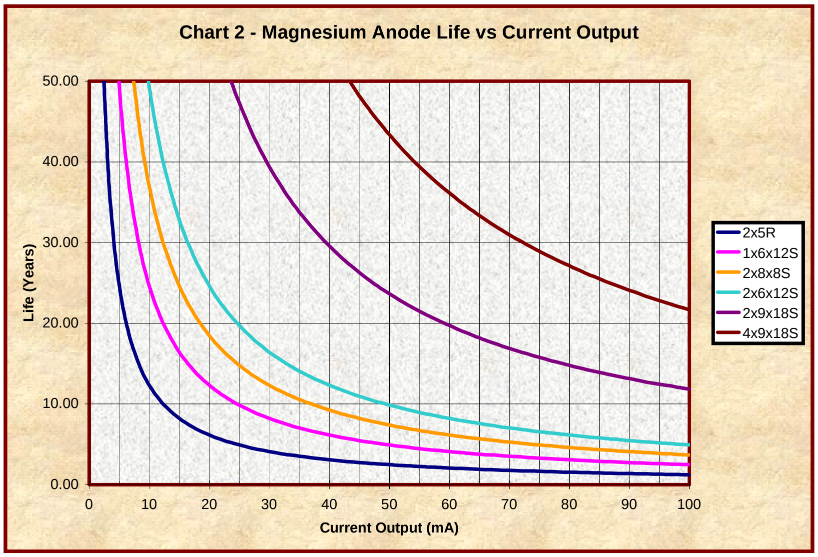


FIGURE C-2. MAGNESIUM ANODE LIFE VERSUS CURRENT OUTPUT

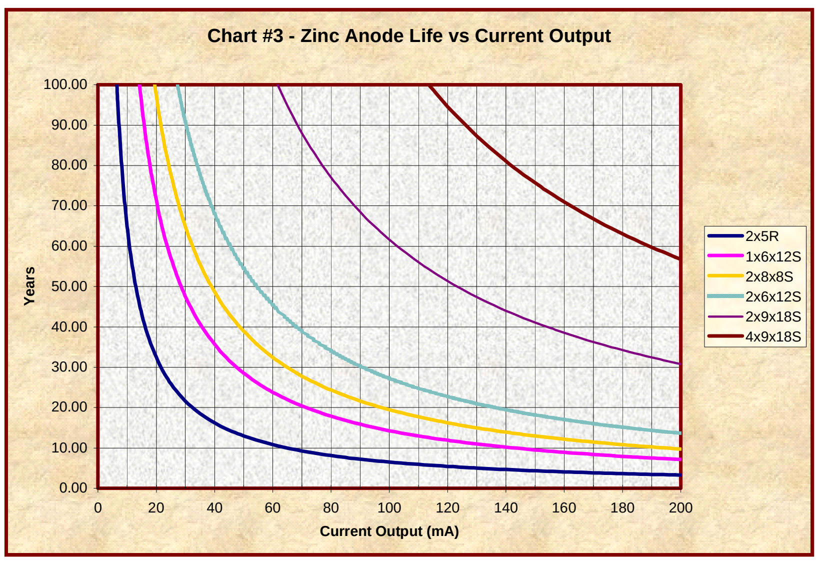


FIGURE C-3. ZINC ANODE LIFE VERSUS CURRENT OUTPUT

As can be seen from Figures C-2 and C-3, only one magnesium anode style has a 20-year life at 100 mA current output. By comparison, there are five zinc anode styles with a 20-year life at 100 mA and two at 200 mA. However, zinc is capable of delivering this higher current only in very low-resistivity water (usually brackish or salt water).

In summary, magnesium is preferred in higher resistivity waters (above 2000 ohm-cm) while zinc will almost always be preferred in waters below 1000 ohm-cm. For water above 3000 ohm-cm, high-potential magnesium will generally be preferred, and from 1500 to 2000 ohm-cm, H-1 Alloy will almost always be preferred. Table C-3 will help in this general selection process.

TABLE C-3. PREFERRED ALLOYS FOR VARIOUS RESISTIVITY WATERS

(Best = ✓✓✓)							
Water Resistivity (Ohm-Cm)	**< 500**	**>500 to 1000**	**>1000 to 1500**	**>1500 to 2000**	**>2000 to 2500**	**>2500 to 3500**	**>3500**
high-potential Magnesium				✓	✓✓	✓✓✓	✓✓✓
H-1 Alloy, Grade A or B Magnesium			✓	✓✓	✓✓✓	✓✓	✓
high-purity Zinc	✓✓✓	✓✓	✓✓	✓			

With respect to current output of each anode style, charts can be developed for specific resistivity environments. Generally, fresh water river and lake water will have resistivity values between 1000 ohm-cm and 3000 ohm-cm. Tables C-4 – C-9 list in detail the current output for each anode style. These tables include a visual plot of the data for comparison purposes. The water resistivity values used in these tables range from 1000 ohm-cm to 4000 ohm-cm, in increments of 500 ohm-cm.

TABLE C-4. ANODE CURRENT OUTPUT
IN 1000 OHM-CM RESISTIVITY WATER

Anode Style	high-potential Mag	H-1 Mag	high-purity Zinc
2x5RBE	55.88	41.18	14.71
2x5RCE	33.10	24.39	8.71
1x6x12SBE	84.07	61.95	22.12
1x6x12SCE	67.38	49.65	17.73
2x8x8SBE	92.23	67.96	24.27
2x8x8SCE	63.33	46.67	16.67
2x6x12SBE	98.96	72.92	26.04
2x6x12SCE	67.38	49.65	17.73
2x9x18SBE	139.7	102.9	36.77
2x9x18SCE	105.6	77.78	27.78
4x9x18SBE	166.7	122.8	43.86
4x9x18SCE	105.6	77.78	27.78

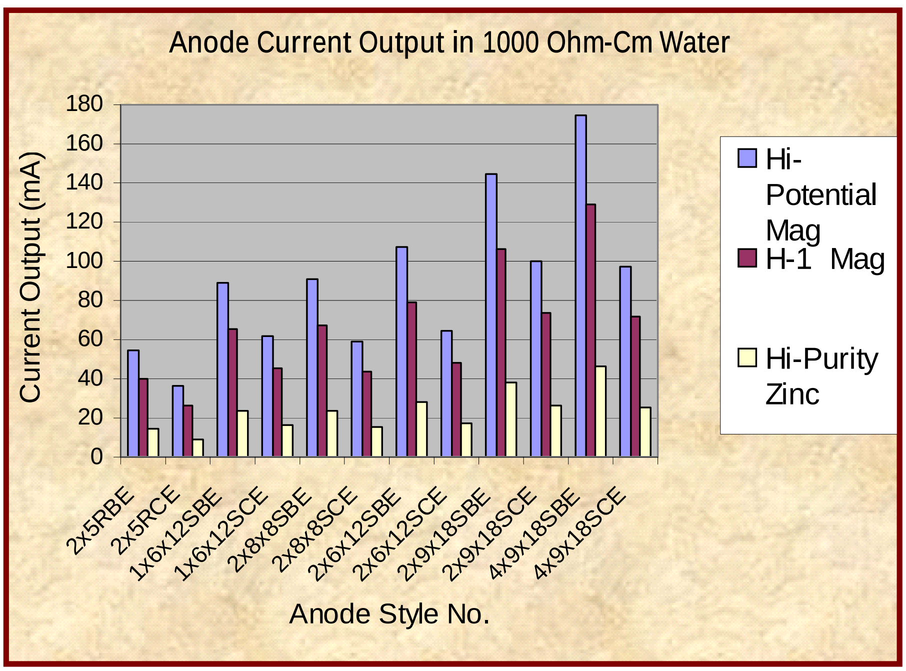


TABLE C-5. ANODE CURRENT OUTPUT
IN 1500 OHM-CM RESISTIVITY WATER

	high-potential Mag	H-1 Mag	high-purity Zinc
2x5RBE	37.25	27.45	9.80
2x5RCE	22.07	16.26	5.81
1x6x12SBE	56.05	41.30	14.75
1x6x12SCE	44.92	33.10	11.82
2x8x8SBE	61.49	45.31	16.18
2x8x8SCE	42.22	31.11	11.11
2x6x12SBE	65.97	48.61	17.36
2x6x12SCE	44.92	33.10	11.82
2x9x18SBE	93.14	68.63	24.51
2x9x18SCE	70.37	51.85	18.52
4x9x18SBE	111.1	81.87	29.24
4x9x18SCE	70.37	51.85	18.52

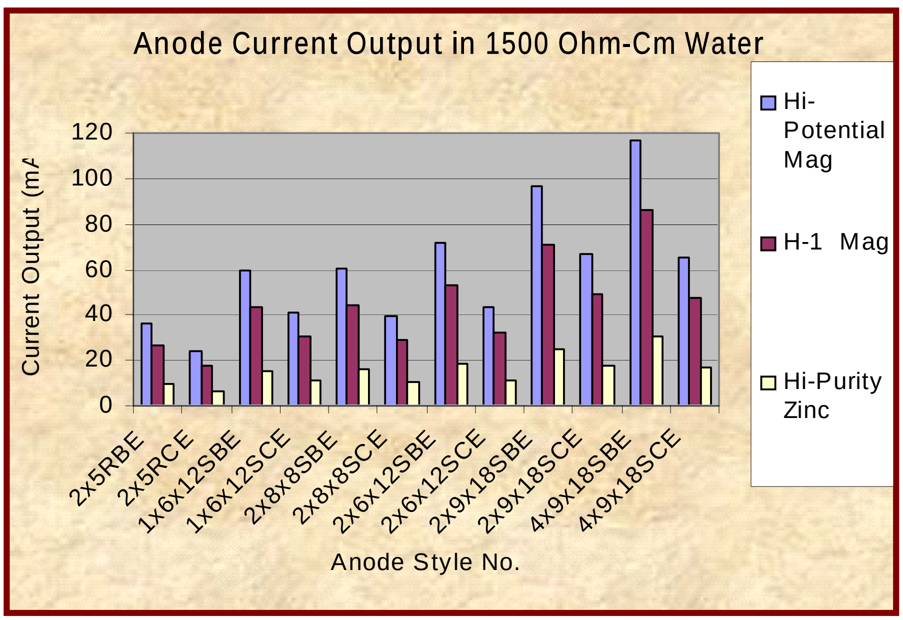
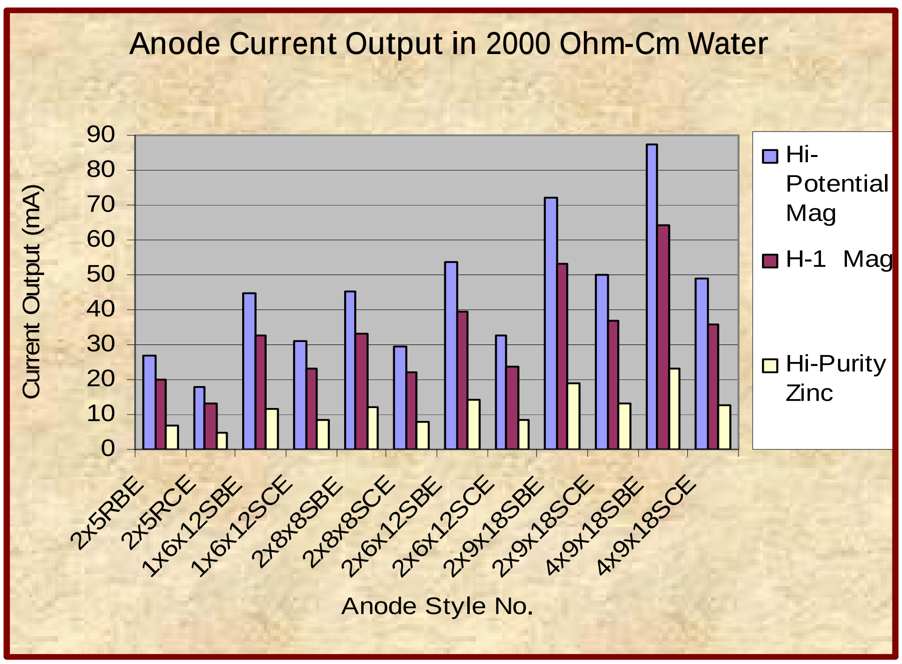


TABLE C-6. ANODE CURRENT OUTPUT
IN 2000 OHM-CM RESISTIVITY WATER

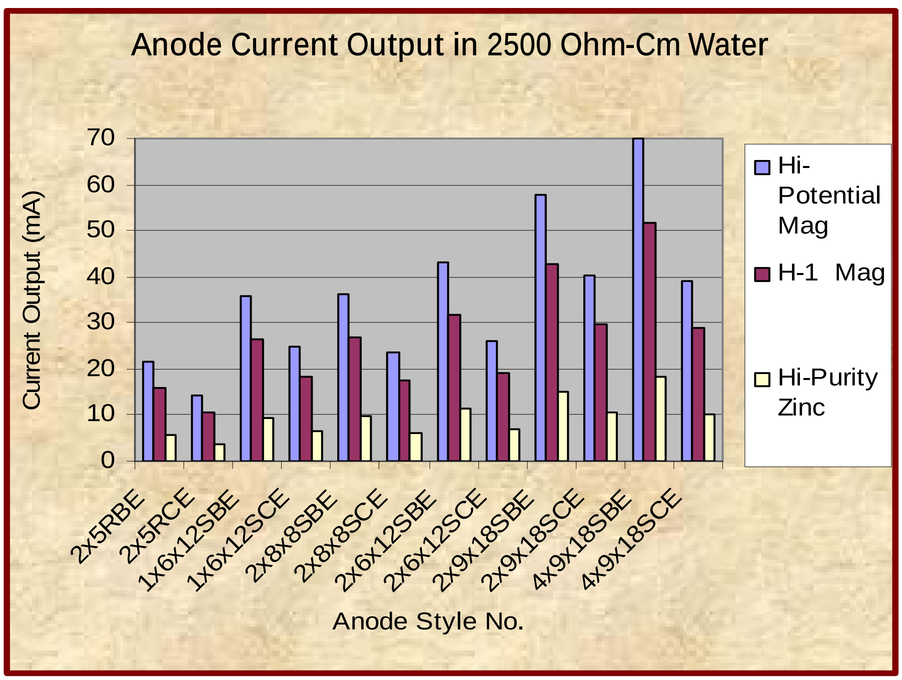
	high-potential Mag	H-1 Mag	high-purity Zinc*
2x5RBE	27.94	20.59	7.35
2x5RCE	16.55	12.20	4.36
1x6x12SBE	42.04	30.97	11.06
1x6x12SCE	33.69	24.82	8.87
2x8x8SBE	46.12	33.98	12.14
2x8x8SCE	31.67	23.33	8.33
2x6x12SBE	49.48	36.46	13.02
2x6x12SCE	33.69	24.82	8.87
2x9x18SBE	69.85	51.47	18.38
2x9x18SCE	52.78	38.89	13.89
4x9x18SBE	83.33	61.40	21.93
4x9x18SCE	52.78	38.89	13.89



* Use of zinc anodes in waters above 2000 ohm-cm is not recommended.

TABLE C-7. ANODE CURRENT OUTPUT
IN 2500 OHM-CM RESISTIVITY WATER

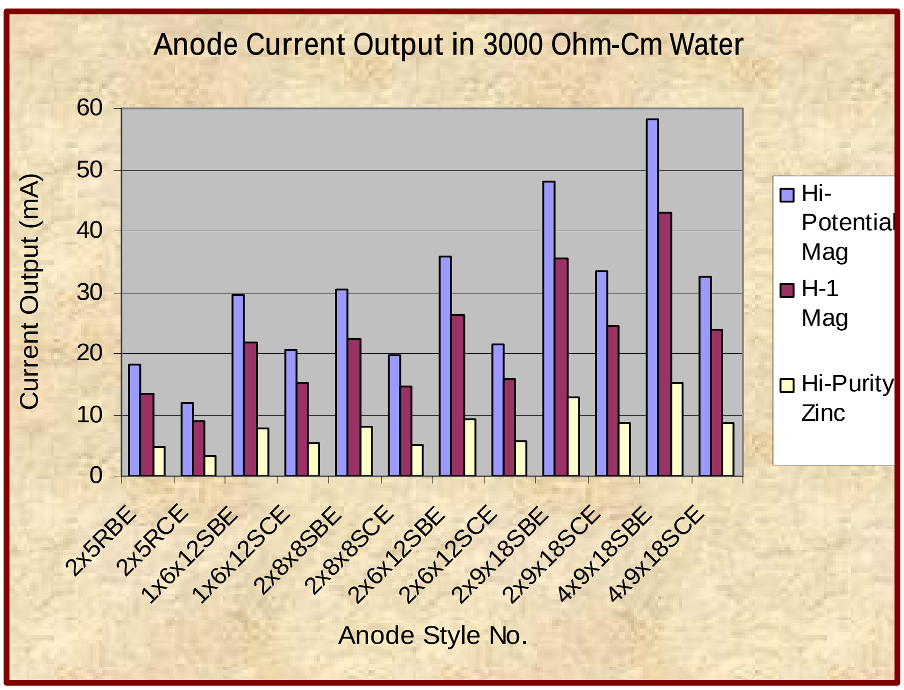
	high-potential Mag	H-1 Mag	high-purity Zinc*
2x5RBE	22.35	16.47	5.88
2x5RCE	13.24	9.76	3.48
1x6x12SBE	33.63	24.78	8.85
1x6x12SCE	26.95	19.86	7.09
2x8x8SBE	36.89	27.18	9.71
2x8x8SCE	25.33	18.67	6.67
2x6x12SBE	39.58	29.17	10.42
2x6x12SCE	26.95	19.86	7.09
2x9x18SBE	55.88	41.18	14.71
2x9x18SCE	42.22	31.11	11.11
4x9x18SBE	66.67	49.12	17.54
4x9x18SCE	42.22	31.11	11.11



* Use of zinc anodes in waters above 2000 ohm-cm is not recommended.

TABLE C-8. ANODE CURRENT OUTPUT
IN 3000 OHM-CM RESISTIVITY WATER

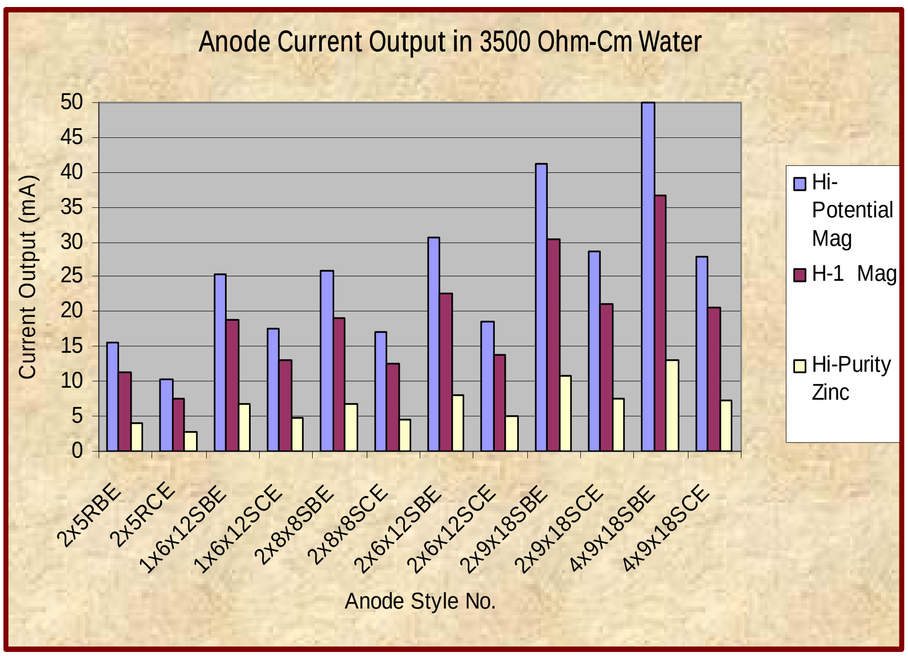
	high-potential Mag	H-1 Mag	high-purity Zinc*
2x5RBE	18.63	13.73	4.90
2x5RCE	11.03	8.13	2.90
1x6x12SBE	28.02	20.65	7.37
1x6x12SCE	22.46	16.55	5.91
2x8x8SBE	30.74	22.65	8.09
2x8x8SCE	21.11	15.56	5.56
2x6x12SBE	32.99	24.31	8.68
2x6x12SCE	22.46	16.55	5.91
2x9x18SBE	46.57	34.31	12.26
2x9x18SCE	35.19	25.93	9.26
4x9x18SBE	55.56	40.94	14.62
4x9x18SCE	35.19	25.93	9.26



* Use of zinc anodes in waters above 2000 ohm-cm is not recommended.

TABLE C-9. ANODE CURRENT OUTPUT
IN 3500 OHM-CM RESISTIVITY WATER

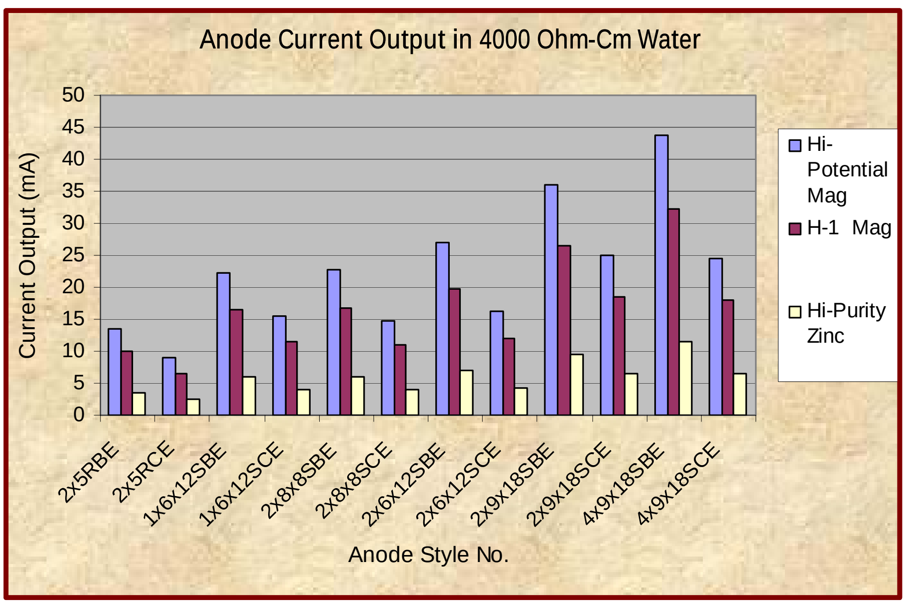
	high-potential Mag	H-1 Mag	high-purity Zinc*
2x5RBE	15.97	11.76	4.20
2x5RCE	9.46	6.97	2.49
1x6x12SBE	24.02	17.70	6.32
1x6x12SCE	19.25	14.18	5.07
2x8x8SBE	26.35	19.42	6.93
2x8x8SCE	18.10	13.33	4.76
2x6x12SBE	28.27	20.83	7.44
2x6x12SCE	19.25	14.18	5.07
2x9x18SBE	39.92	29.41	10.50
2x9x18SCE	30.16	22.22	7.94
4x9x18SBE	47.62	35.09	12.53
4x9x18SCE	30.16	22.22	7.94



* Use of zinc anodes in waters above 2000 ohm-cm is not recommended.

TABLE C-10. ANODE CURRENT OUTPUT
IN 4000 OHM-CM RESISTIVITY WATER

	high-potential Mag	**H-1 Mag**	**high-purity Zinc***
2x5RBE	13.97	10.29	3.68
2x5RCE	8.28	6.10	2.18
1x6x12SBE	21.02	15.49	5.53
1x6x12SCE	16.84	12.41	4.43
2x8x8SBE	23.06	16.99	6.07
2x8x8SCE	15.83	11.67	4.17
2x6x12SBE	24.74	18.23	6.51
2x6x12SCE	16.84	12.41	4.43
2x9x18SBE	34.93	25.74	9.19
2x9x18SCE	26.39	19.44	6.94
4x9x18SBE	41.67	30.70	10.97
4x9x18SCE	26.39	19.44	6.94



* Use of zinc anodes in waters above 2000 ohm-cm is not recommended.